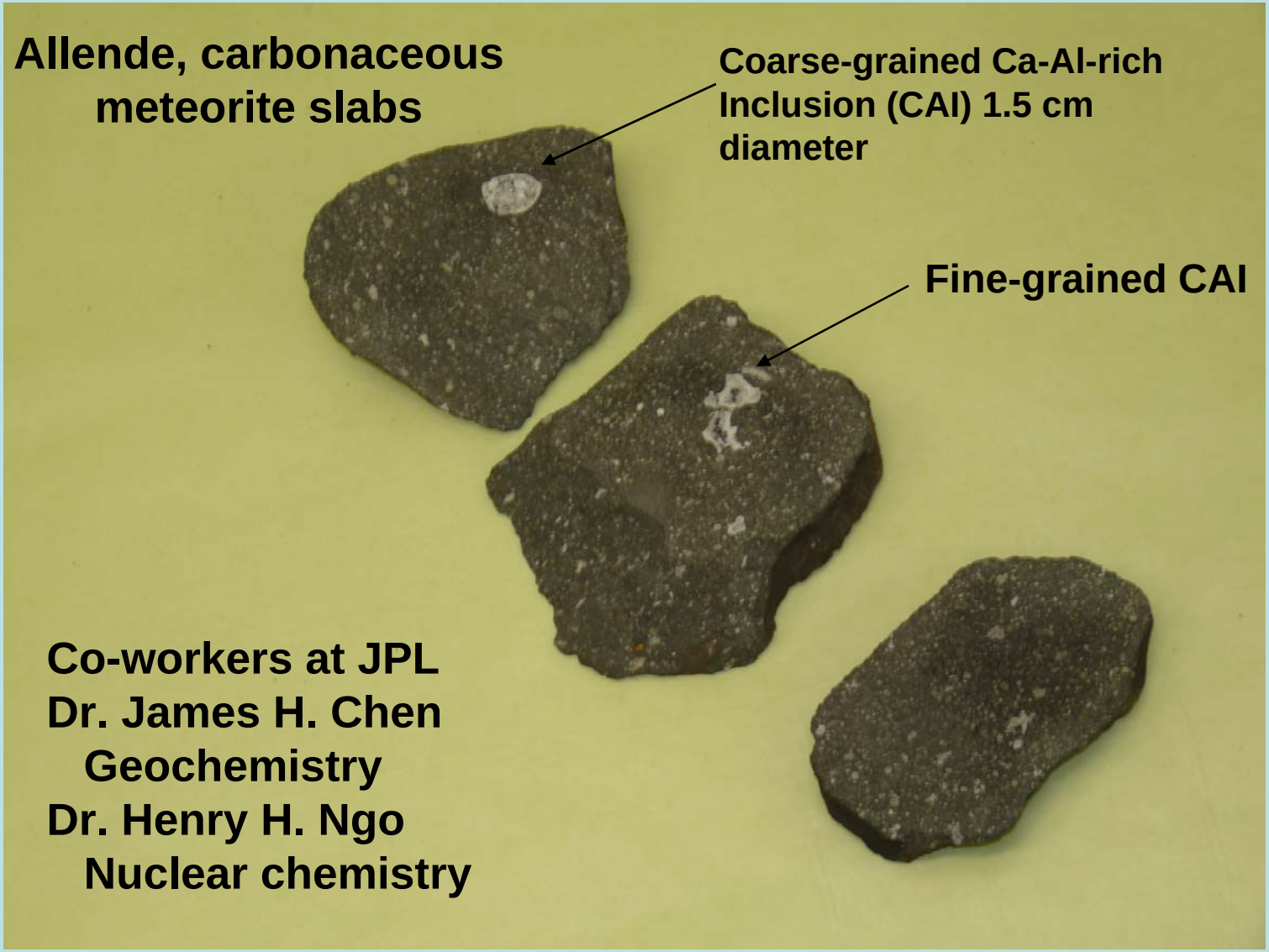
SOLAR SYSTEM CHRONOLOGIES

Dimitri A. Papanastassiou, JPL



Ages

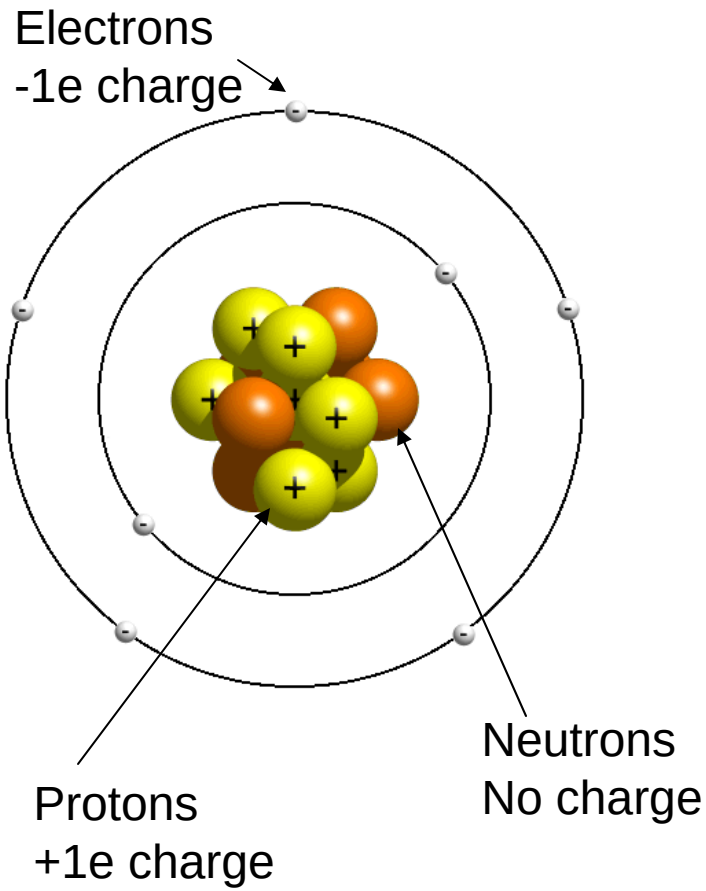
- Everyone wants to know about the age of an artifact, a building, a person, a geologic formation
- An age is fundamental for establishing
  - the time and sequence of events
  - the rates of processes on the Earth, Moon and other solar system bodies

PURPOSE OF THE TALK

- Describe the use of radioactive parent - stable daughter pairs to calculate ages
- Describe the nature of the samples and how they are handled and processed for an age determination
- Give examples for
  - Identification and dating of primitive samples, those formed early in the solar system history and at high temperatures
  - The chronology of the Moon and why we want to bring back again (robotically, this time) thousands of additional samples, 45 years after Apollo
- These are current active research areas; but I will show some of the data of the first discoveries and only a very limited review of current work

Age Dating of Rocks

- Before the discovery of radioactivity
  - Ages were based on sediment stratification or on how long it would take the Earth to cool
  - Fossils helped compare relative time sequences and major events
  - All dating was relative and absolute age estimates were wrong
- After the discovery of radioactivity
  - Radioactive-parent - daughter systems used
  - Valid absolute ages and age differences measured, by multiple chronometers



CLASSIC PICTURE OF AN ATOM
ELECTRONS orbit the NUCLEUS
(nucleus not drawn to scale!)

Nitrogen: 7 protons and 7 electrons
^{14}N: 7 neutrons
^{15}N: 8 neutrons

ISOTOPES

- Atoms with the same number of PROTONS (and ELECTRONS) define an ELEMENT and its CHEMISTRY

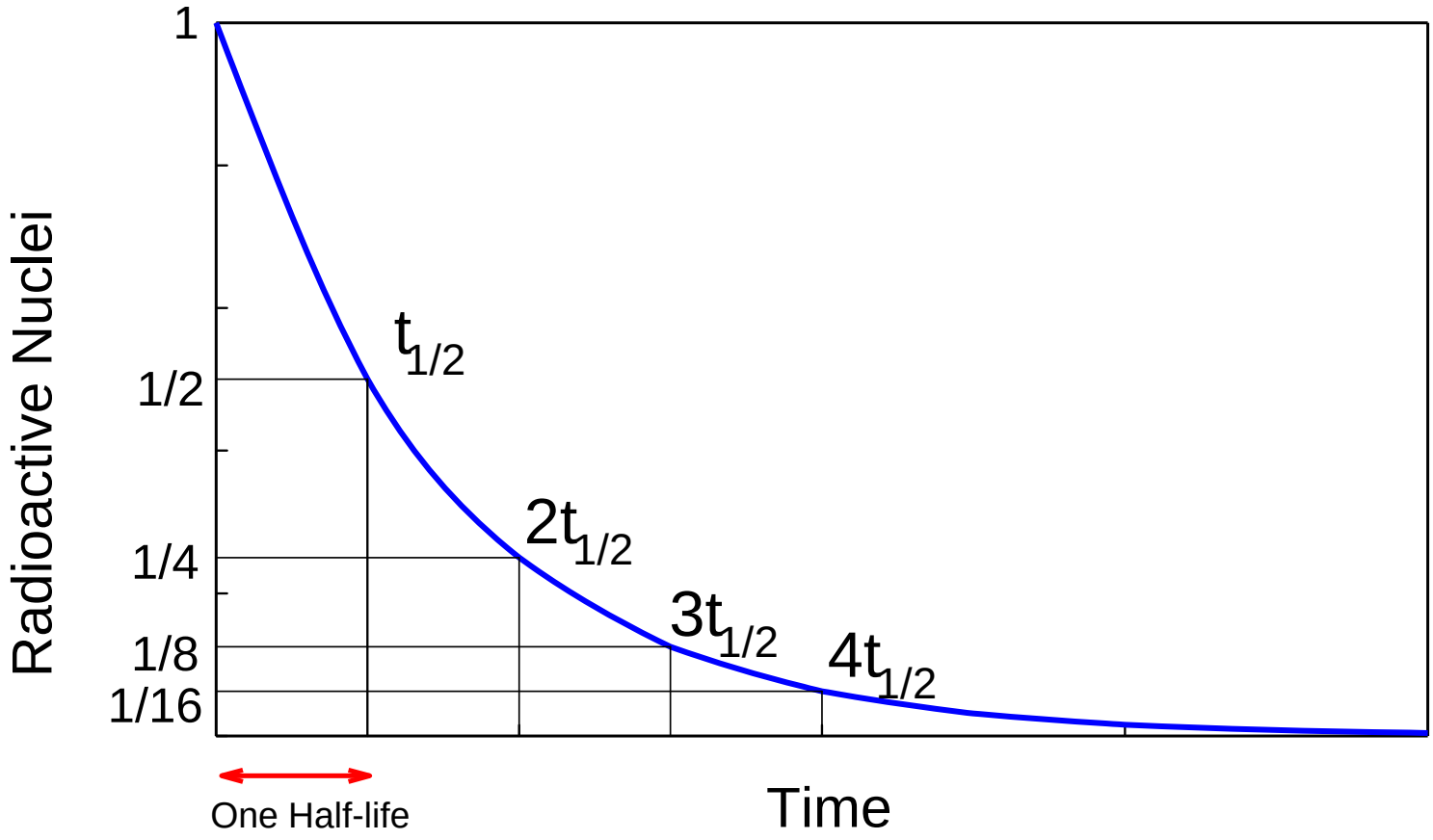
- Atoms with the SAME NUMBER OF PROTONS and DIFFERENT NUMBER OF NEUTRONS are ISOTOPES of that element

- ISOTOPES of each element have the same chemical properties but different nuclear properties and ATOMIC MASSES, and can be separated and measured by a mass spectrometer

- Some isotopes are unstable (subject to radioactive decay)

Radioactive Decay

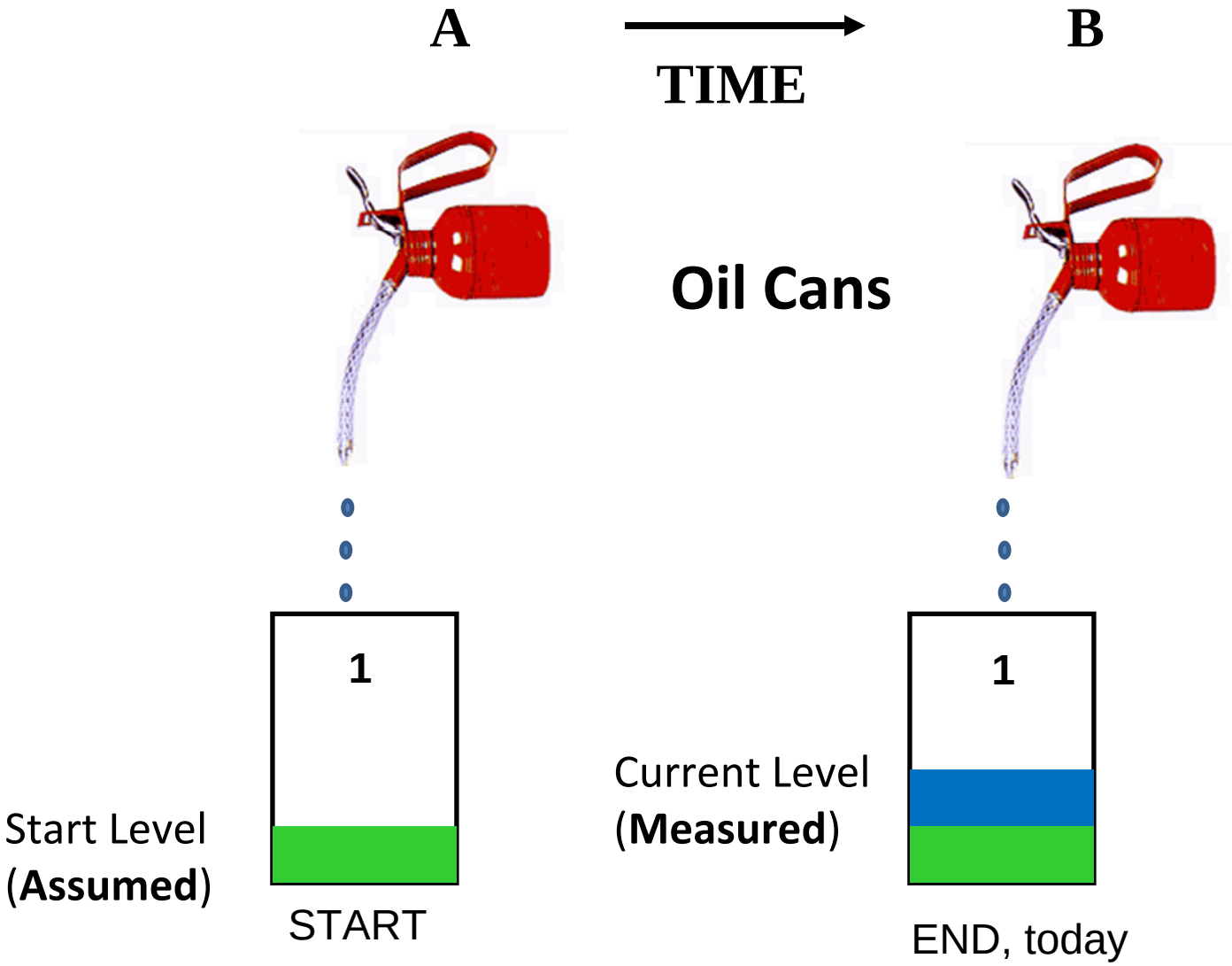
Definition of Half-life ($t_{1/2}$)



Successive half-lives decrease the number of undecayed nuclei by half each time

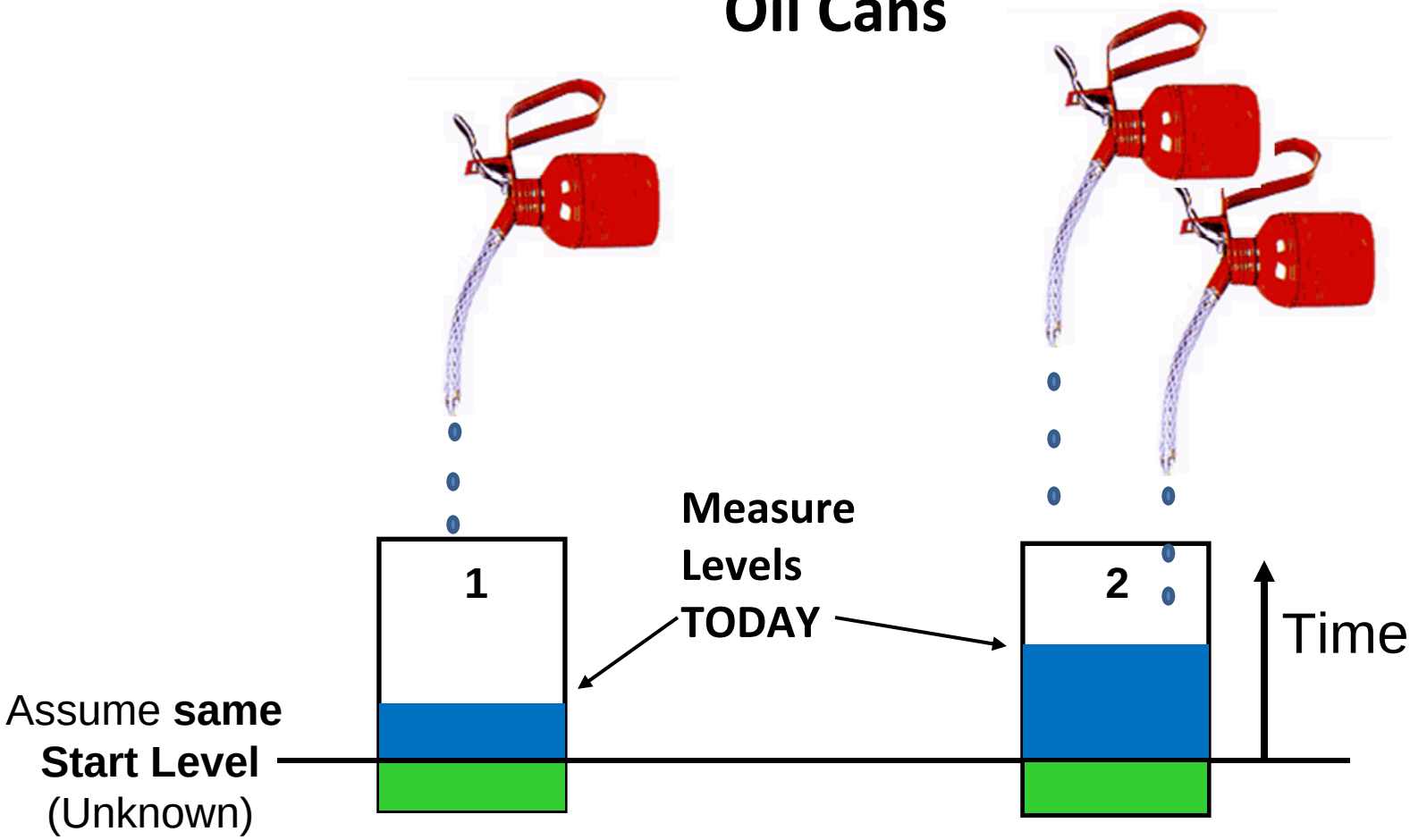
RADIOACTIVE PARENT - DAUGHTER ISOTOPE DATING

SIMPLE ANALOGUES / CARTOONS



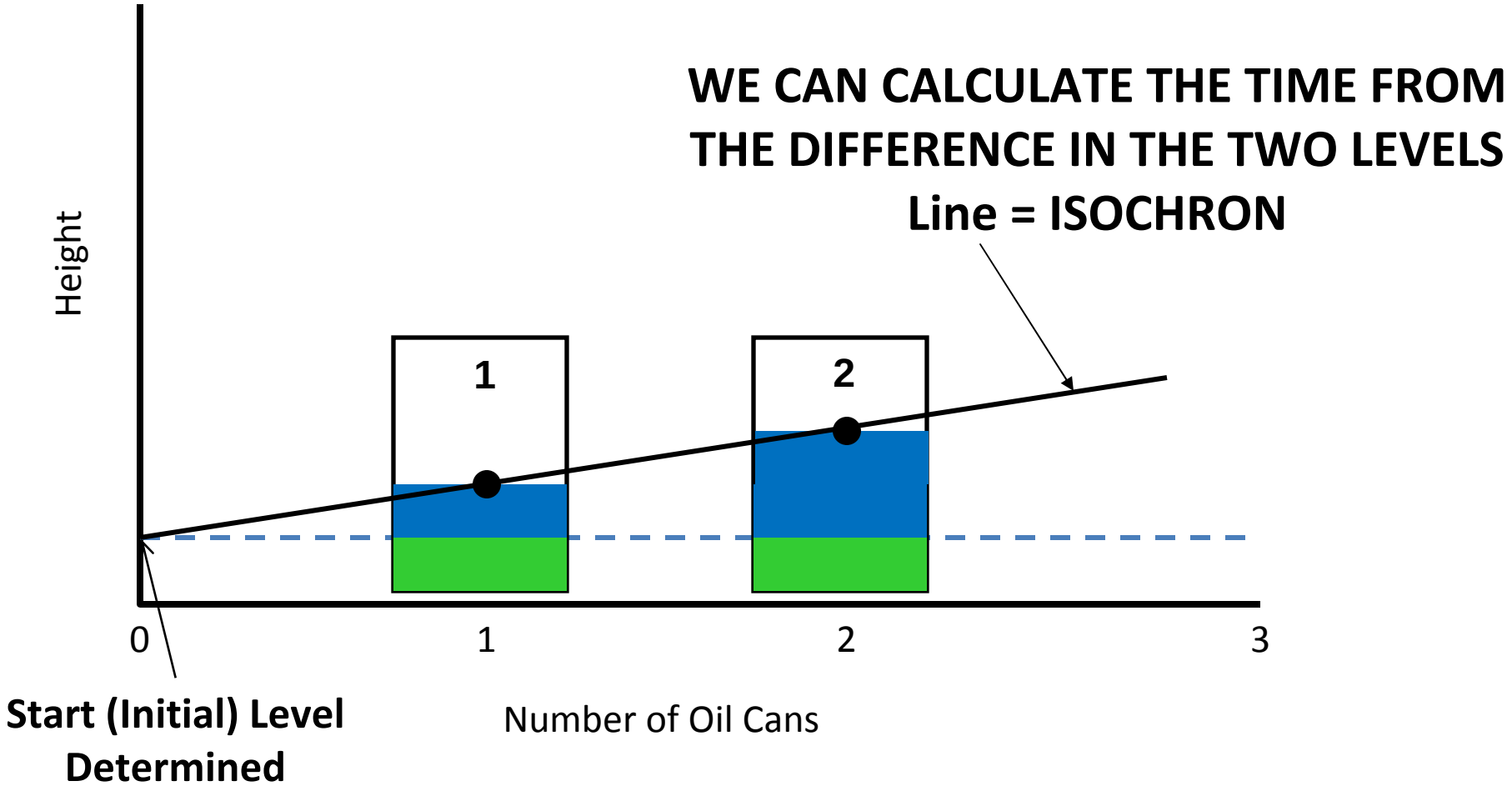
Calculate the AGE from the difference in levels and constant drip rate

Oil Cans



Calculate AGE and Start Level from both systems and constant drip rate

ISO-CHRON MEANS SAME-AGE (In Greek)

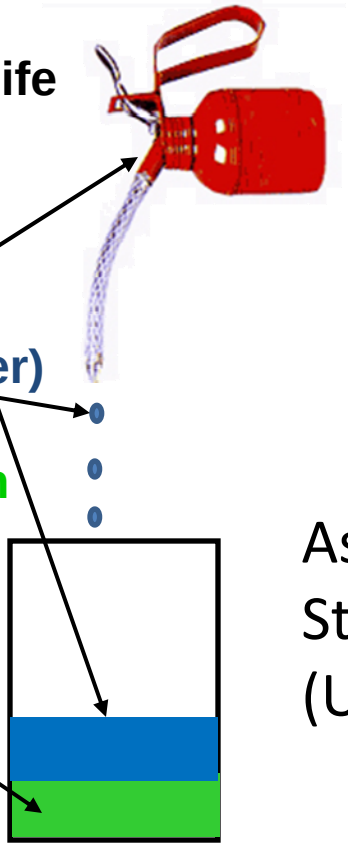


Radioactive Parent-Stable Daughter Systems

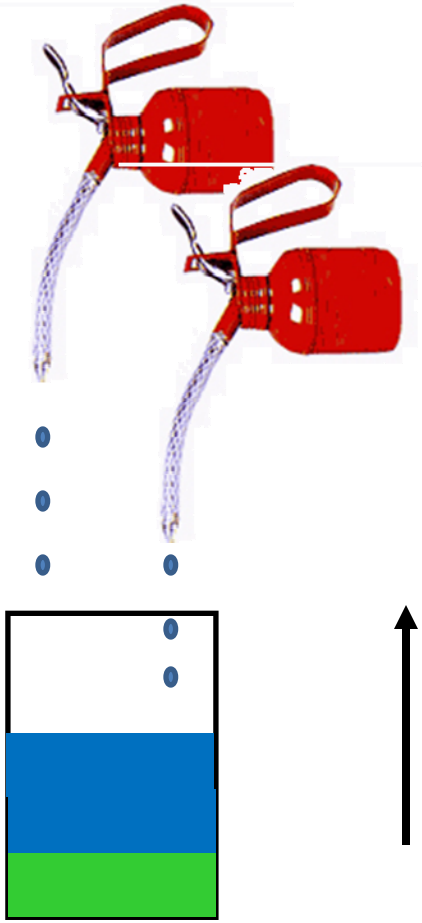
Example: ^{87}Rb decays into ^{87}Sr

"Oil Can" = ^{87}Rb
Drip Rate = Half-life
~50 billion years

^{87}Rb = red (Parent)
^{87}Sr = blue (Daughter)
^{87}Sr at start green
Also ^{86}Sr, ^{88}Sr green at start



Assume Same Start Level (Unknown)



Time

Calculate age and ^{87}Sr at start by measuring both systems and a constant drip rate

This an ISOCHRON Age

ONE MORE OIL CAN ANALOGY!

Drip rate “constant” = drip rate is in a constant proportion to the amount of OIL remaining in the cans

SHORT-LIVED PARENT

“Drip” stops (empty oil can)
After a few Million years

LONG-LIVED PARENT

“Drip” rate continues over the age of the solar system (4.56 Billion years)

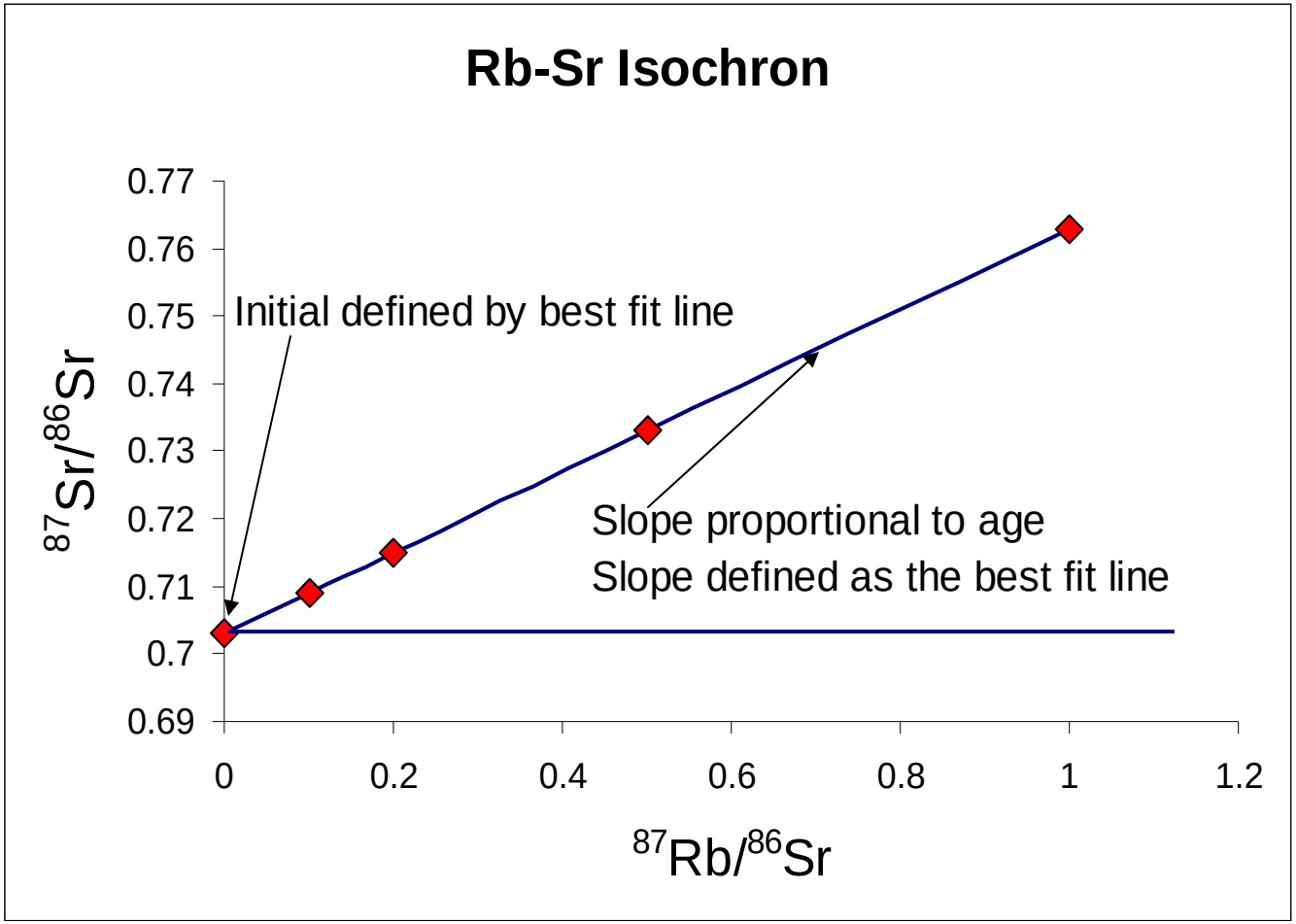
For ^{87}Rb, with a half-life of about 50 Billion years only about 9% of the initial ^{87}Rb has decayed

FORGET “oil cans” and think of them as incorporated in minerals in rocks
We NEED minerals with a range in parent / daughter element ratios

WE SEPARATE AND MEASURE MINERALS FROM A ROCK

AND DETERMINE ISOCHRON AGES

Internal Isochron



Minerals with a range in $^{87}Rb/^{86}Sr$ are necessary and must to be found, separated, and analyzed

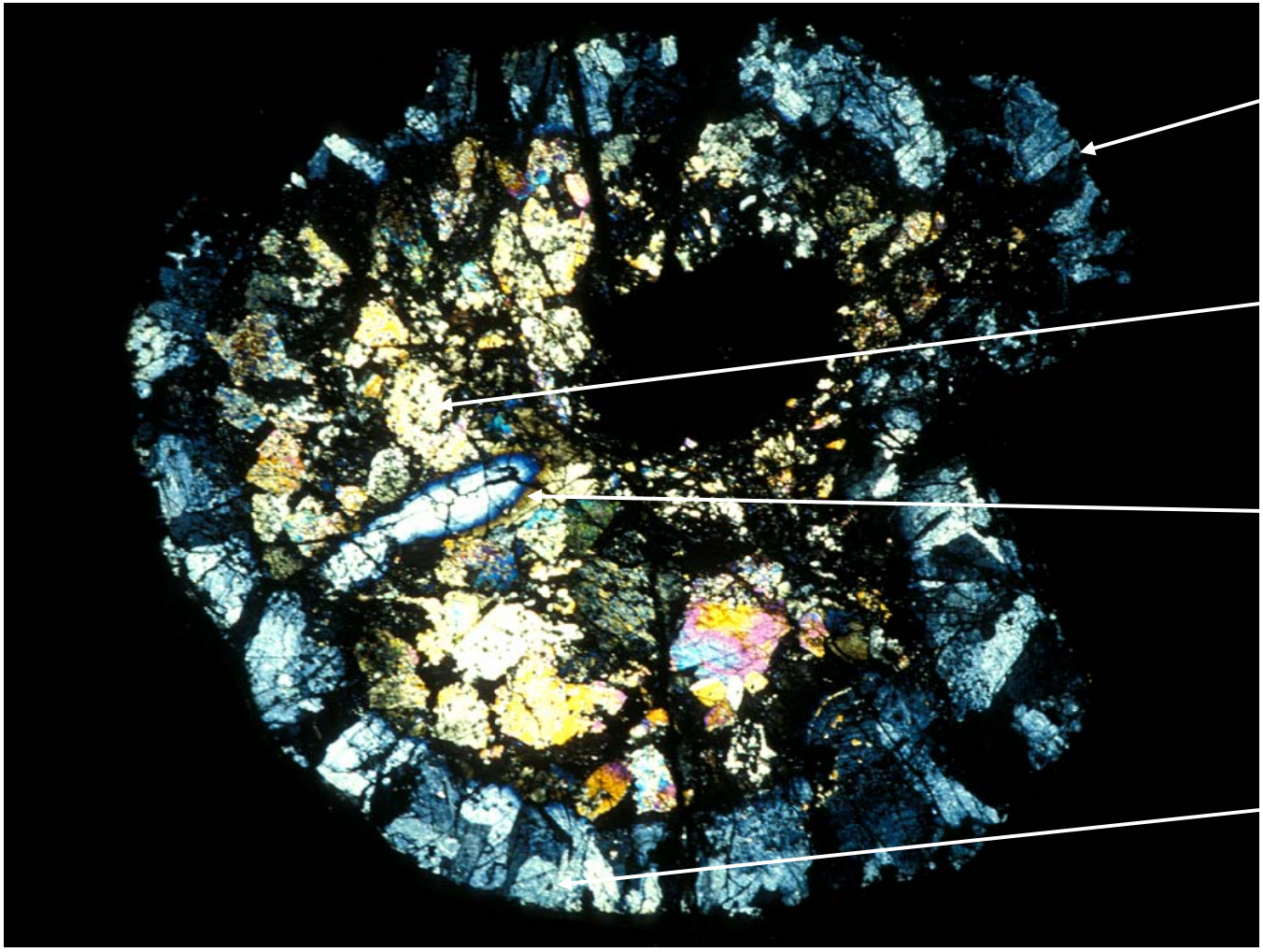
Outline of Talk

- What it takes to measure an age (and why returned samples are necessary)
- Short-lived chronometers
- Long-lived Rb-Sr and Sm-Nd on the Moon
- U-Pb on the Moon and the Terminal Lunar Cataclysm
- Going back to the Moon (robotically)
  - The New Frontiers MoonRise mission proposal and the Solar System-wide Late Bombardment

Slabs of the Allende Meteorite

Slices for the purpose of finding
large Ca-Al-rich refractory inclusions

Thin Section of an extracted Allende Ca-Al-rich Inclusion (view under a petrographic microscope)



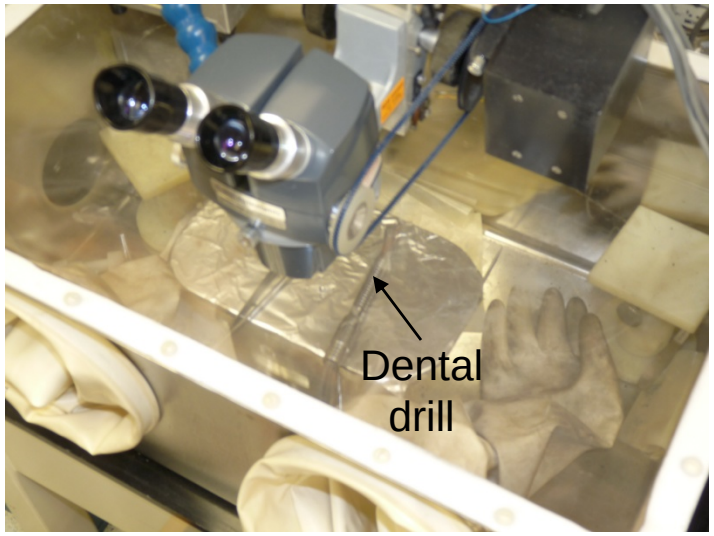
Grey mantle
Melilite

Colorful Interior
Fassaite

Plagioclase laths

Dark specks of
Spinel in all the
major minerals

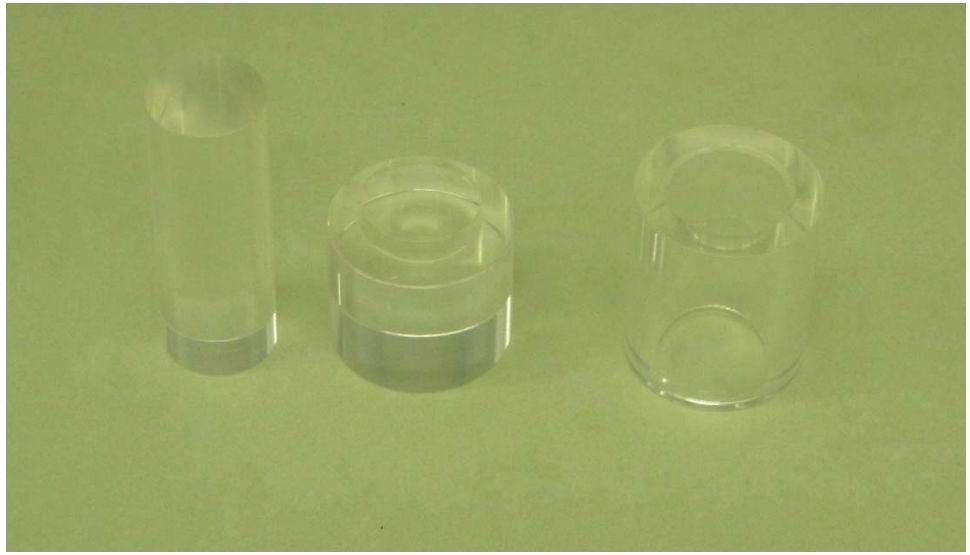
Courtesy, Dr. Glenn J. MacPherson, NMNH, Smithsonian



Extract sample (using dental drill)

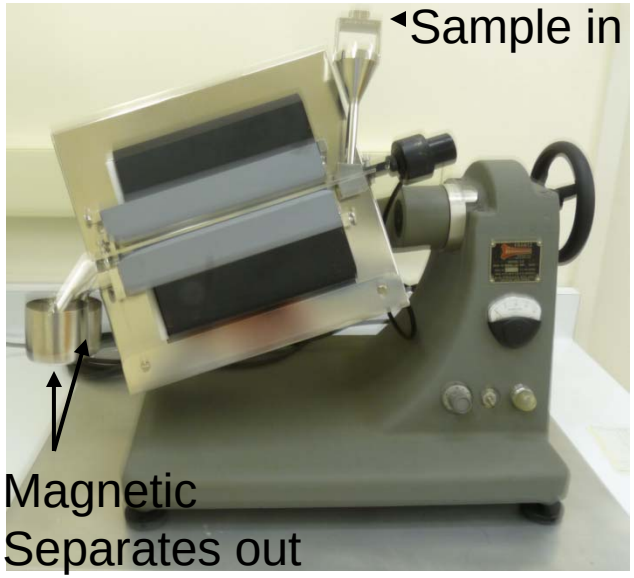
Stainless mortar and pestle (not quite like at home)

Assemble and Crush



Sapphire mortar and pestle for ultra clean U-Pb work

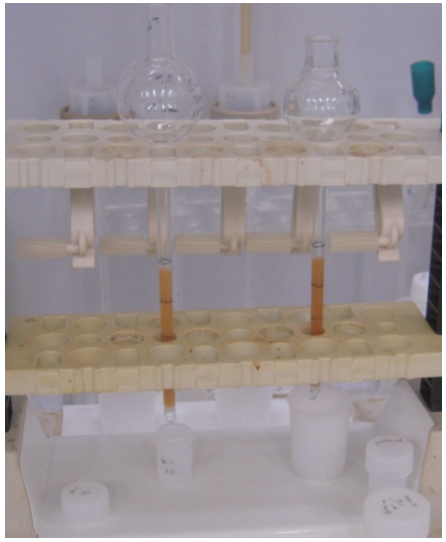
Weigh sample



Magnetic separation of minerals

Hand-pick crystals

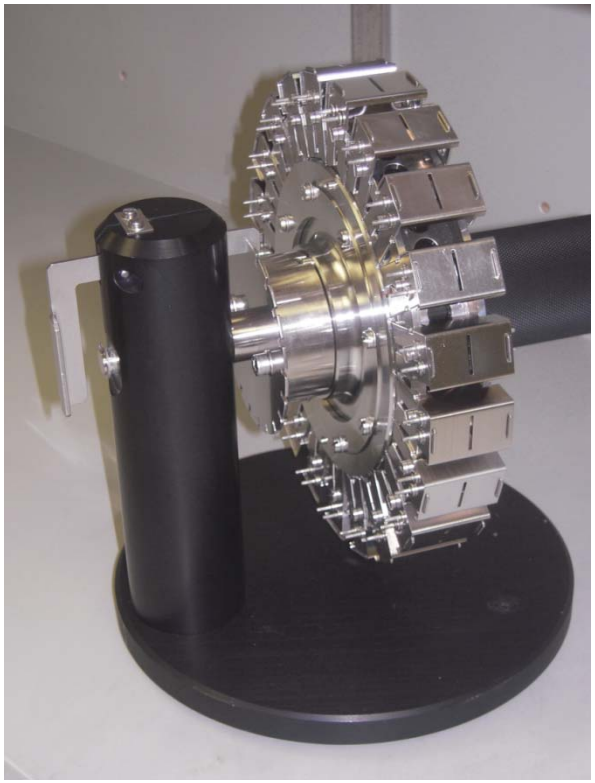
Dissolve sample



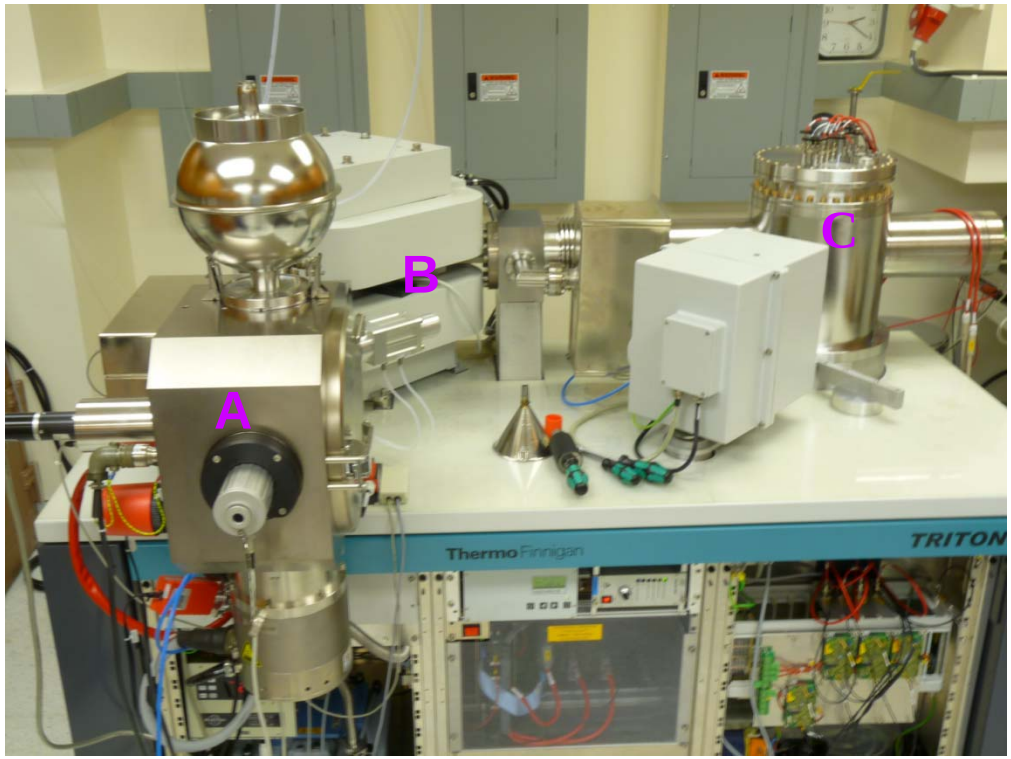
Separate elements
by ion exchange

Dry element solutions

Mass Spectrometry



Samples loaded on filament assemblies on a turret



TRITON mass spectrometer
A: Sample chamber; B: Magnet; C: Ion collectors

CONCLUSION: Dating of samples requires high precision and many types of exquisite analytical capabilities

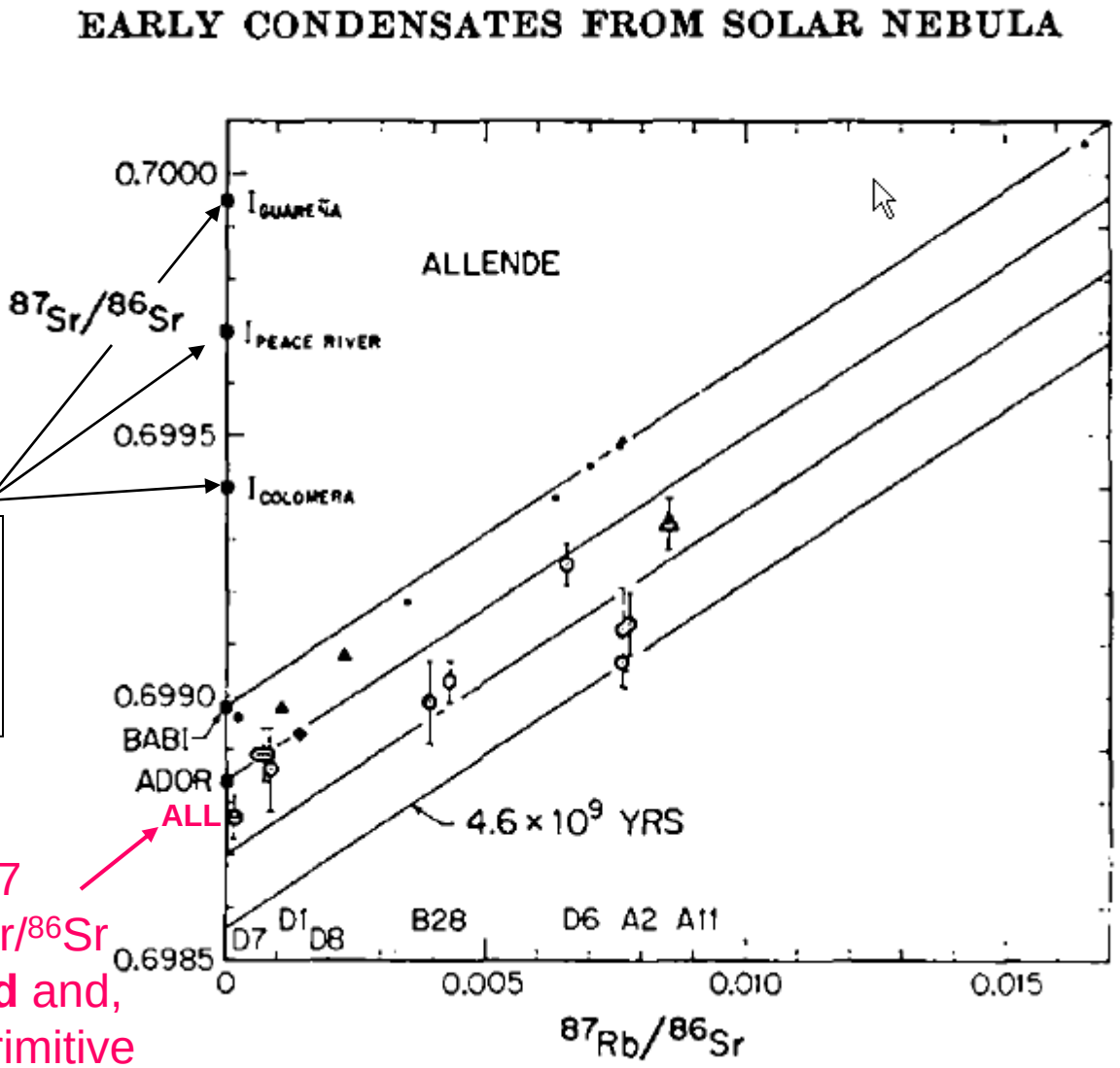
The Art of Finding Primitive Samples

- Finding and proving the most primitive (unaltered) and early-formed samples
- 1969 was a very good year
  - Apollo 11 samples returned, July 24
  - Two primitive, carbonaceous meteorites **observed to fall** on Earth

The Allende meteorite (Feb. 8, in Northern Mexico)

The Murchison meteorite (Sept. 28, in Australia)

ALLENDE AS A PRIMITIVE METEORITE
First isotopic evidence



From other Meteorites 100 million yr difference

ALLENDE CAI INCLUSION D7 The lowest $^{87}Sr/^{86}Sr$ ever **measured** and, hence, most primitive preserved value

Parallel isochrons (with different Initial $^{87}Sr/^{86}Sr$ ratios)

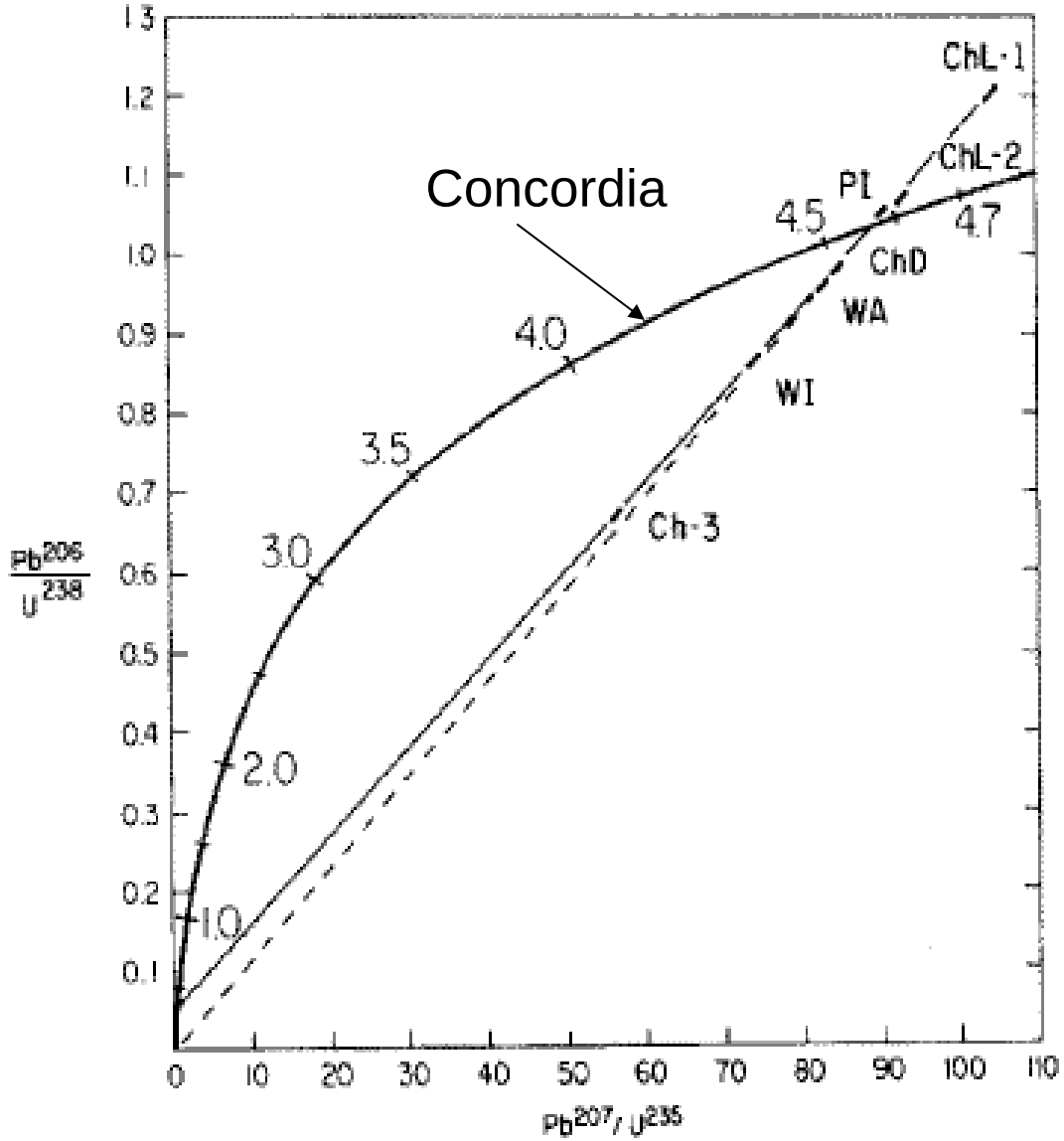
From Gray, Papanastassiou, Wasserburg, 1973

Uranium – Lead Concordia Diagram for Allende CAI

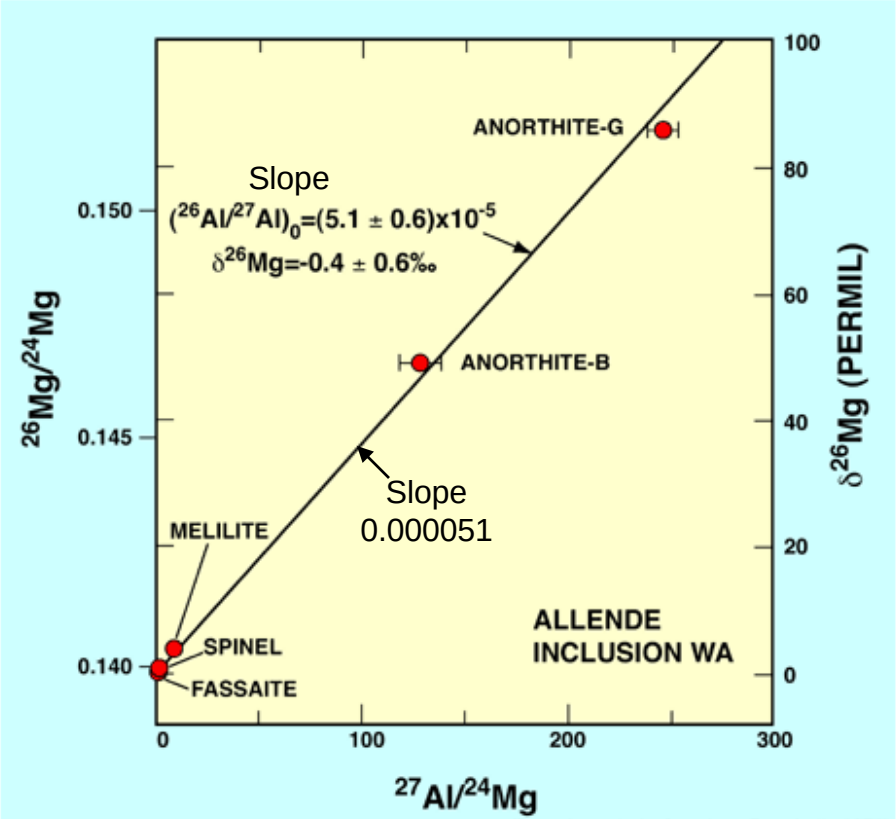
The CONCORDIA curve shows the same age by the coupled U-Pb chronometers: ^{238}U-^{206}Pb, ^{235}U-^{207}Pb

The solid line through the data, intersects the curve at 4.57 billion years. This age establishes the time when the first and most primitive condensates formed in the solar system formed.

(J. Chen and G. Tilton 1976)



Live ^{26}Al and the first ^{26}Al-^{26}Mg internal isochron



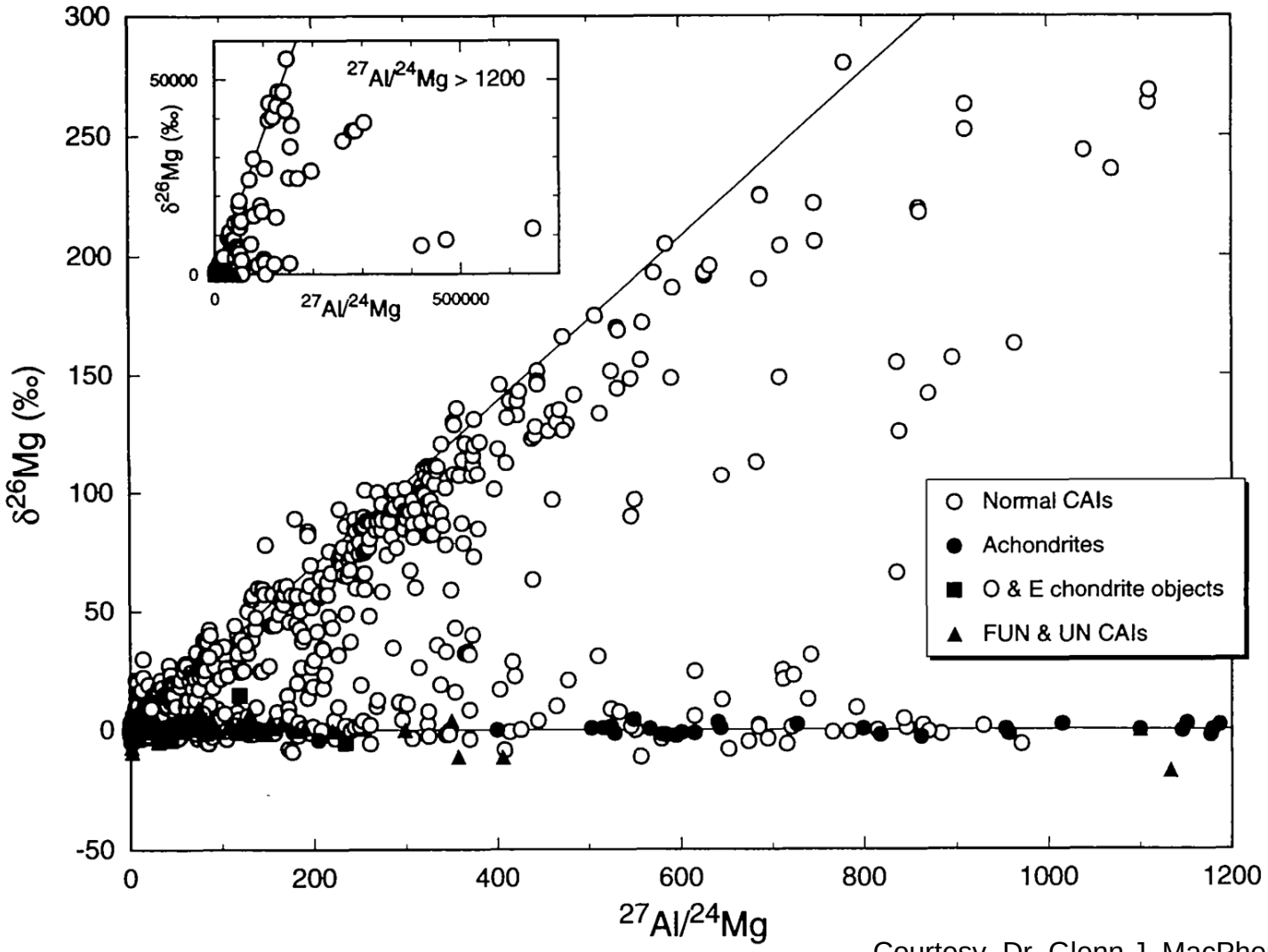
^{26}Al (**half-life of only 0.7 million years**) was proposed as a heat source for planets in 1955, by chemist H. C. Urey.
It took more than 20 years to prove the existence of ^{26}Al, with the right sample

Allende Ca-Al-rich Inclusion WA: A large, unaltered inclusion, which Jim Chen shared after he measured the U-Pb ages

We established the correlation of ^{26}Mg/^{24}Mg excesses and the ^{27}Al/^{24}Mg ratio, on inclusion WA, in 1977

The straight line (isochron) proves that ^{26}Al was alive when the inclusion formed, within a few million years of solar system beginning

^{26}Al-^{26}Mg Chronology Today!



STILL A VERY ACTIVE FIELD

But also,

It is good to have discovered the first evidence for the in situ decay of ^{26}Al and then to have left the infinite details to others and to new instruments

Courtesy, Dr. Glenn J. MacPherson, NMNH, Smithsonian

INDICATORS OF PRIMITIVE SAMPLES

- Enrichment in high temperature (refractory) elements, such as Ca and Al
  - Lowest measured (initial) $^{87}Sr/^{86}Sr$
  - Oldest U-Pb ages (4.57 billion years)
  - Proof for formation when very short-lived radioactive parent atoms were alive, such as ^{26}Al, with a half-life of only 0.7 million years

- ^{26}Al is now extinct in the solar system and in the samples
  - Note: 0.7 million years, 4.57 billion years ago, is like the first 1/2 week of a 40-year old person

- Samples marking the birth of our solar system

We talked about the earliest high-temperature inclusions in the Solar System

NOW

Talk about the chronology of the Moon

GREAT EXPECTATIONS

There were competing theories

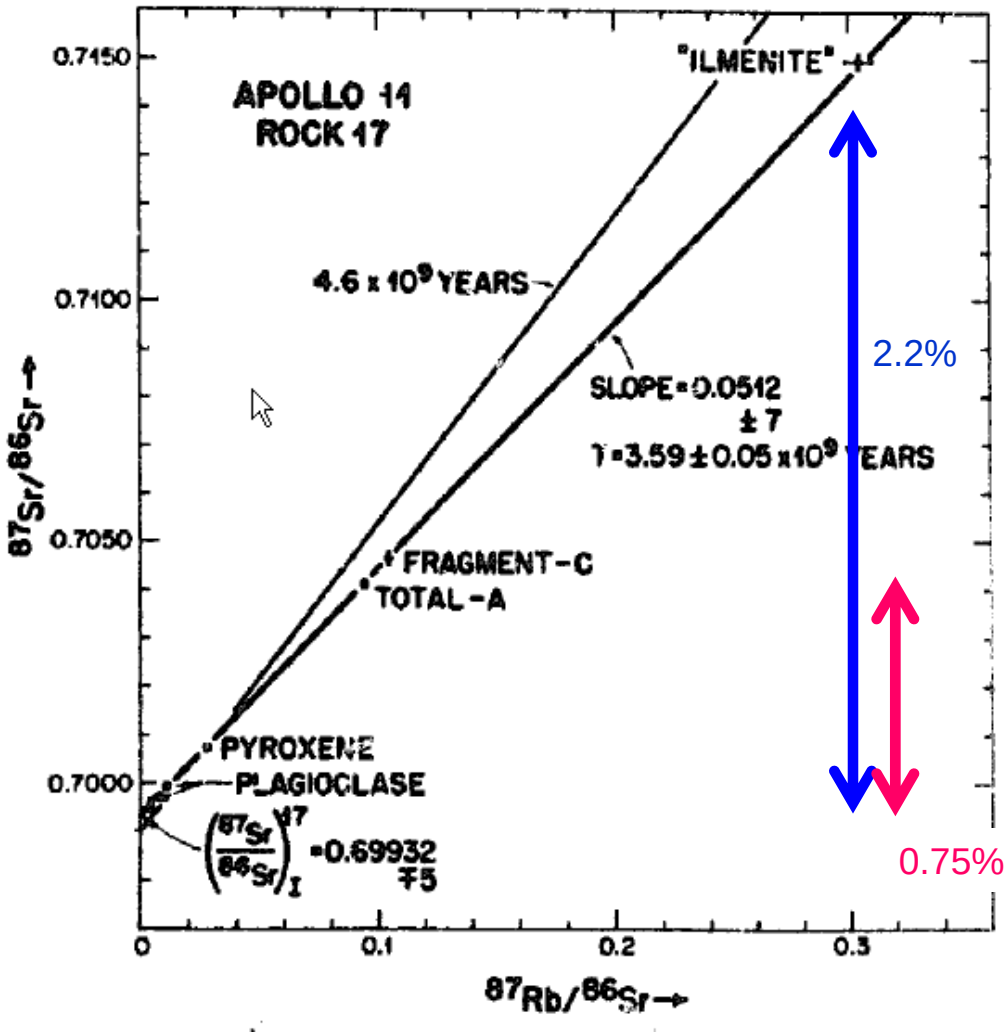
before we got to the Moon; before we returned samples:

- The surface of the Moon was very old, or
- The surface of the Moon was very young

All missed the mark

- There is nothing like actual experimental data to dispel firmly held theories and opinions
- You can not tell time by just looking at the surface and the record on the surface of the Moon from crater forming impacts

Apollo 11 High-K mare basalt
^{87}Rb-^{87}Sr isochron



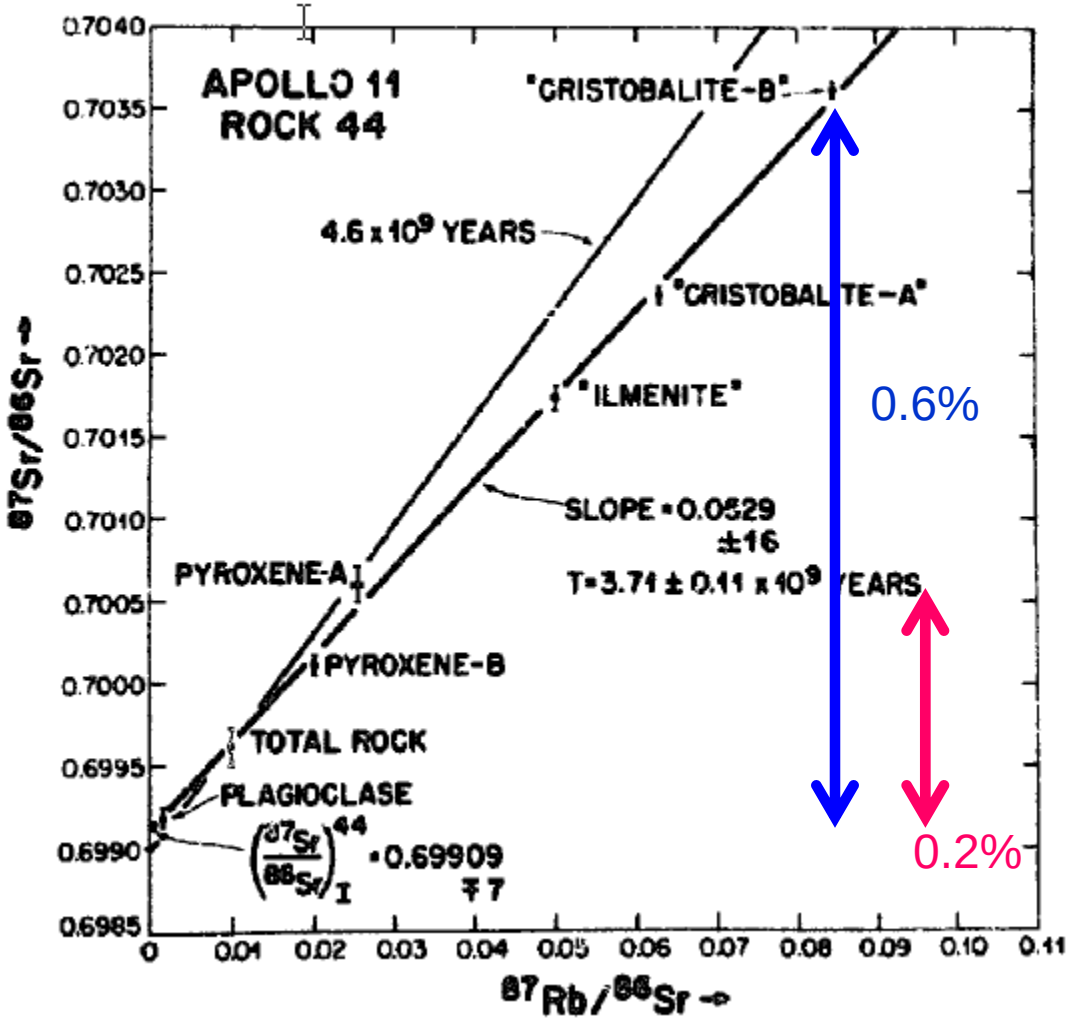
Difficulty:
Small differences in ratios:
Total Range of
$^{87}Sr/^{86}Sr$ = 2.2%

and

$^{87}Sr/^{86}Sr$ = 0.75%
(Major phases and total rock)

DAP et al. 1970

Apollo 11 Low-K mare basalt
^{87}Rb-^{87}Sr isochron



Extreme Difficulty: Very small differences in isotope ratios
Total Range of
$^{87}Sr/^{86}Sr$ = 0.6%

And

$^{87}Sr/^{86}Sr$ = 0.2%
(Major phases and total rock)

DAP et al. 1970

Extreme Difficulty

Range in $^{87}Sr/^{86}Sr$

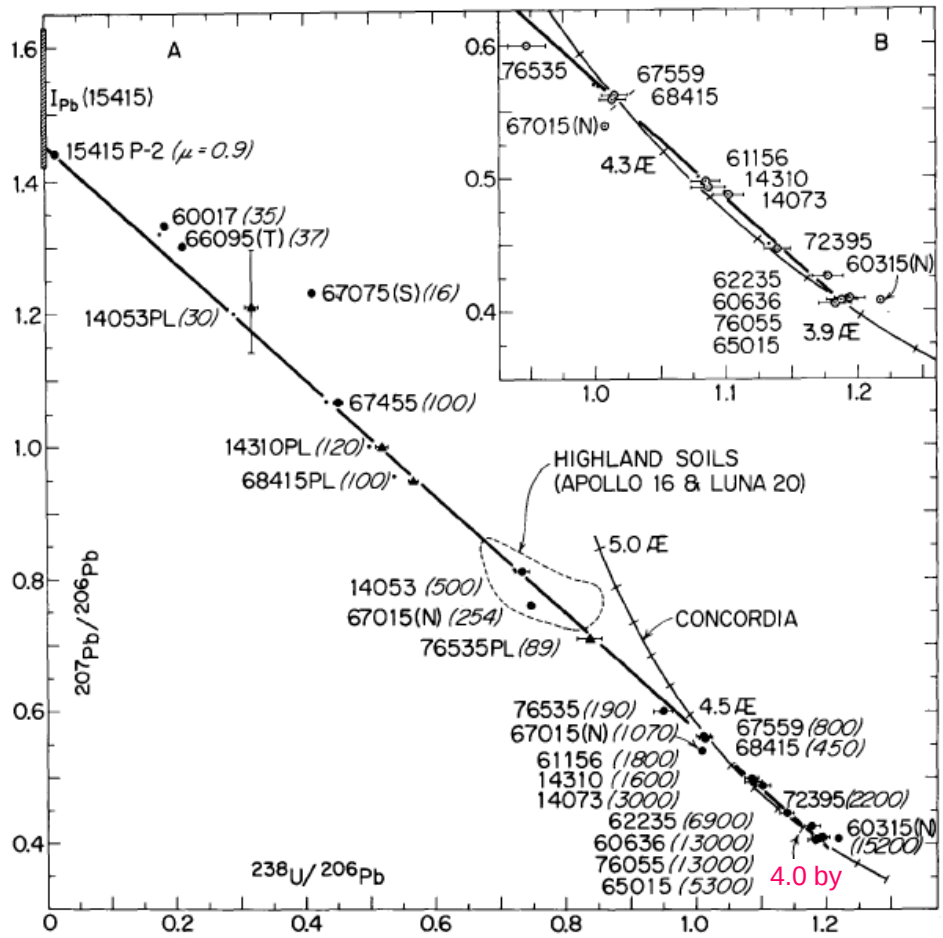
- If the total range in $^{87}Sr/^{86}Sr$ is 0.6%
- And the precision of the data is 0.005%
- Then the precision in the age is (0.005%) / (0.6%) = 0.008 or 0.8%; and closer to 1.2% because we need to combine uncertainties of at least two data points
- 1.2% of a 3.7 billion year age is 45 million years

This means high precision data is a requirement

Current precision is 0.001%, corresponding to an AGE uncertainty of 10 million years

ONE MORE CONCORDIA U–Pb DIAGRAM
Lunar Cataclysm Evidence for a Heavy Bombardment of the Earth, Moon and inner solar system at 3.9-4.0 billion years ago

The data on highland impact melts were interpreted as evidence of a “Terminal” Cataclysm on the Moon at 3.9-4.0 billion years ago, which caused wide-spread melting on the lunar surface and Pb volatilization and then condensation in the new rocks produced by the large impacts.



Note: 1 Æ = 1 aeon = 1 billion years

From ISOTOPIC EVIDENCE FOR A TERMINAL LUNAR CATACLYSM
(Tera, Papanastassiou and Wasserburg (1974) EPSL **22**, pp. 1-21)

LUNAR CHRONOLOGY
From Apollo and Luna Samples

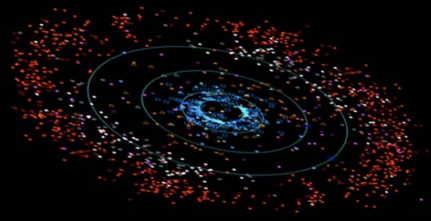
- Moon formed at 4.5 Billion years ago
  - From an impact of a Mars-size body on the Earth when the Earth was about 70% its final size
  - Almost no rocks survive with this age on the Moon
- Mare basalts (in the dark areas on the Moon; impact basins covered by thin volcanic lava flows)
  - Basalt ages range from 3.9 to 3.0 Billion years
- Highland (light areas) samples, many remelted by large impacts on the Moon
  - Ages in the narrow range of 3.9 to 4.0 Billion years
  - Age and formation interpreted as due to a late intense bombardment of the lunar surface

Proposal for Returning Samples from the Moon to Check on the Lunar Terminal Cataclysm and Its Importance for the Solar System

The New Frontiers South Pole-Aitken Basin Sample Return Mission Proposal

PROPOSED LAUNCH IN 2016

~44 YEARS AFTER THE END OF APOLLO

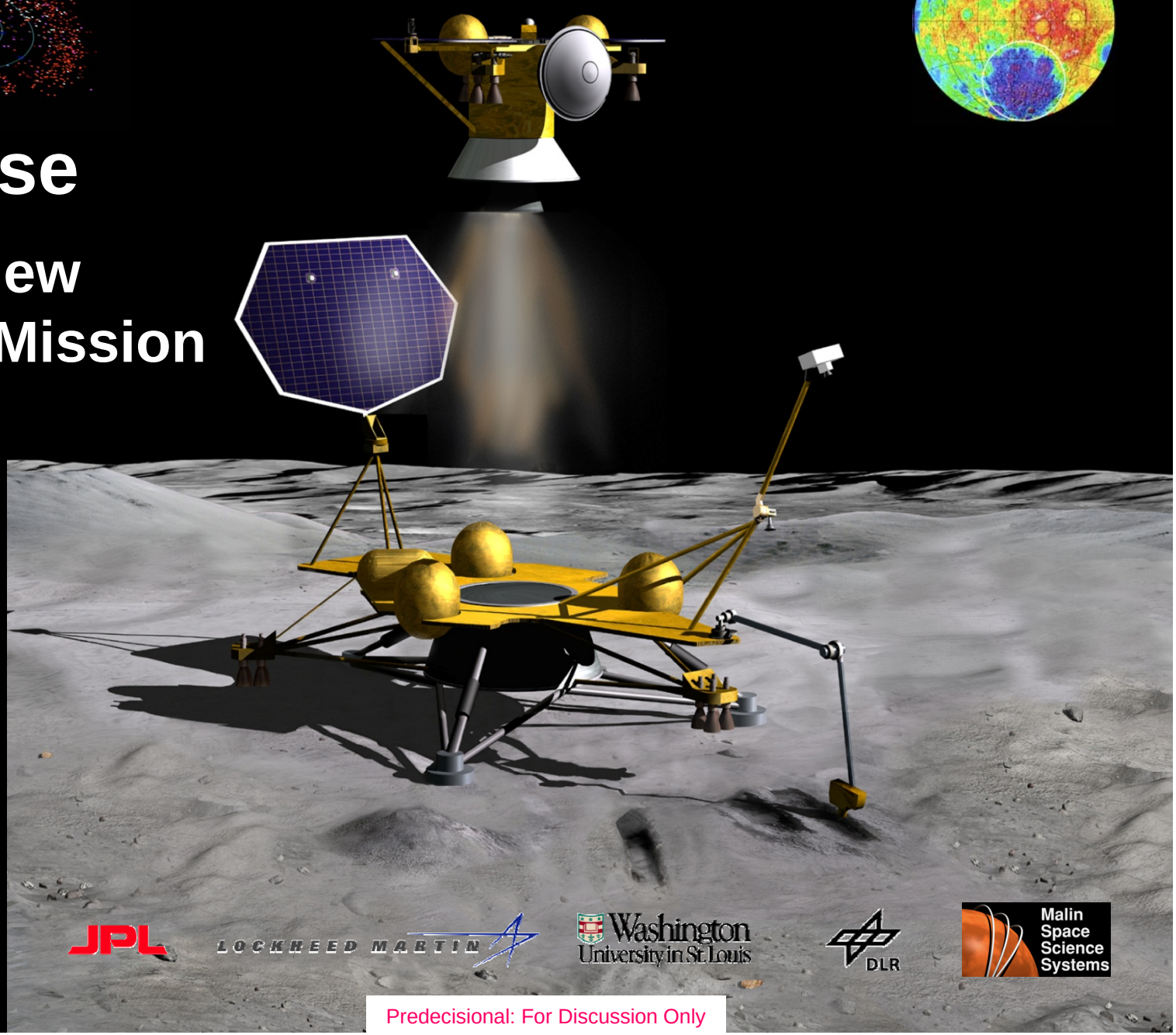


MoonRise

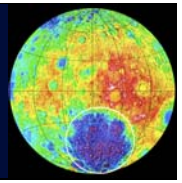
A NASA New Frontiers Mission Proposal

Bradley Jolliff, Washington Univ., St. Louis
Principal Investigator

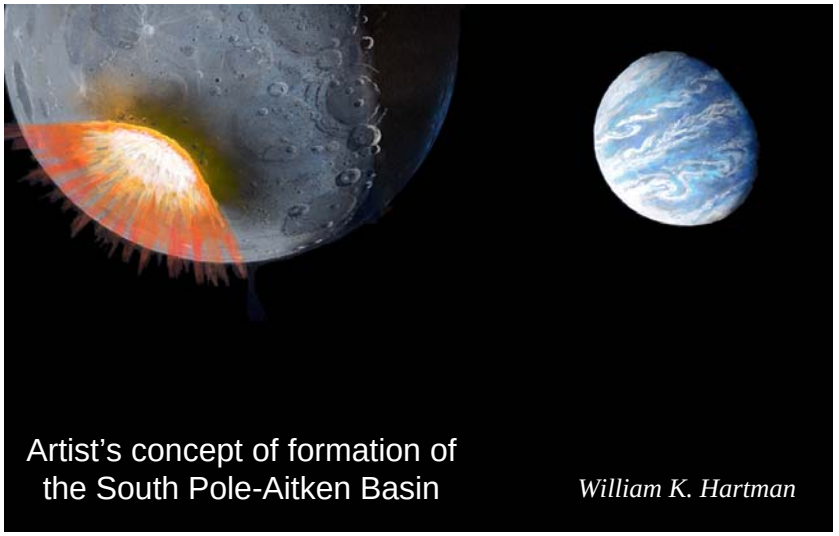
Dimitri Papanastassiou, Jet Propulsion Lab
Project Scientist



MoonRise



- **MoonRise is designed to to address key science objectives:**
  - Determine the age of a key event in Solar System history.
  - Test of the Cataclysm hypothesis for early bombardment of Earth-Moon System
  - Test of hypotheses for early orbital dynamics of gas giant planets
- **MoonRise would test these hypotheses by determining the age of the oldest impact melts and thus the age of the SPA Basin formation.**

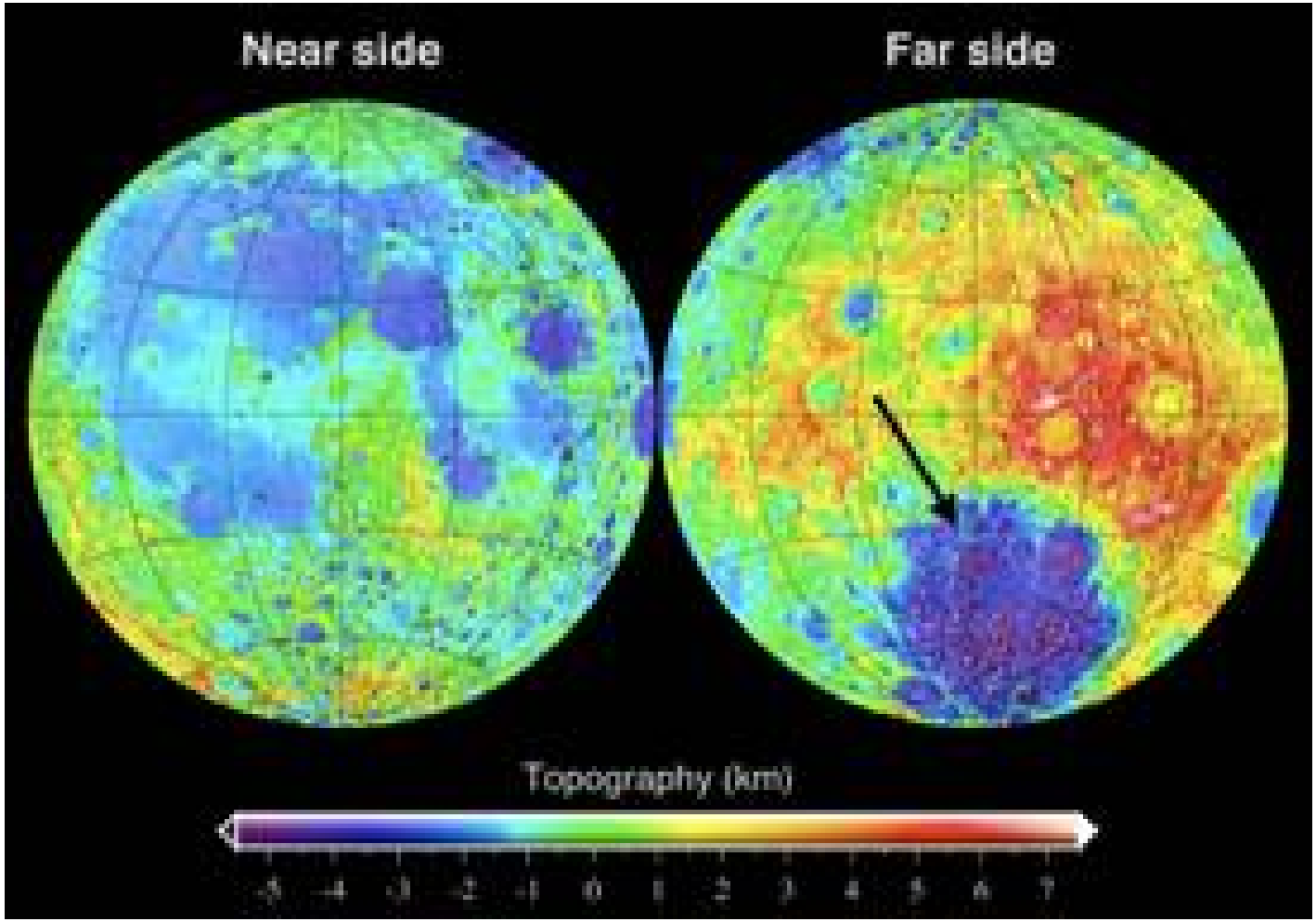


Artist's concept of formation of the South Pole-Aitken Basin

William K. Hartman

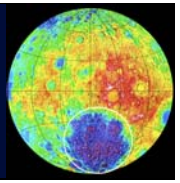
MoonRise would profoundly affect our understanding of the origins and early years of life on Earth.

MoonRise



Kaguya topography data (violet, low topography). The SPA basin (arrow)

MoonRise addresses key Solar-System science

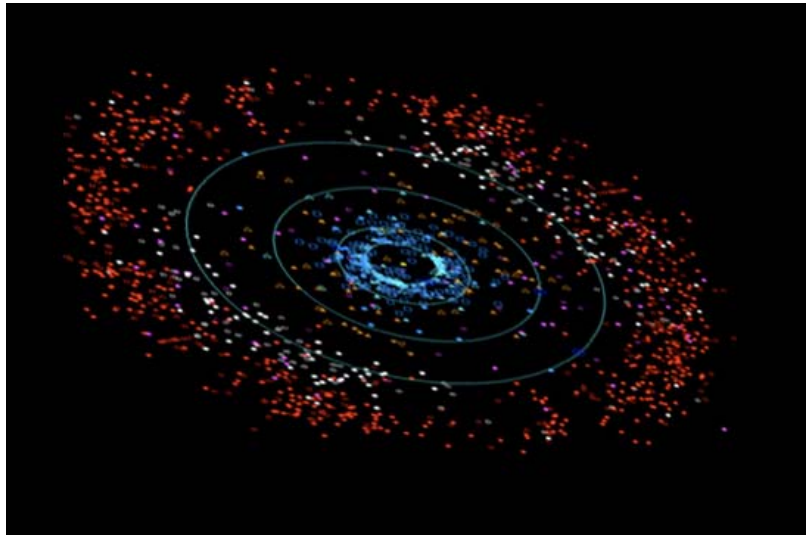


- **Apollo samples show that Moon and Earth experienced a late, heavy bombardment or "Terminal Cataclysm"**

  ~ 3.9 to 4.0 billion years ago

- **Current dynamical models indicate that a shift in orbits of the gas giants could have caused the injection of asteroids and comets into the inner Solar System at about 500 m.y. following planetary accretion.**

- **Materials of the SPA Basin hold the key to the impact Cataclysm and thus what happened on the Earth and Moon in their first ~500 million years.**

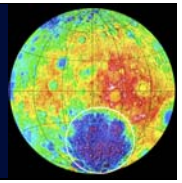


Artistic rendering of objects in the Solar System including gas giant orbits (green) and objects of the inner Kuiper Belt (red).

Solar System relevance:

- **Test models of orbital dynamics in the early Solar System**
- **What caused the release of small orbiting bodies to the Inner Solar System?**
- **What were the effects on the development of habitable environments and life on Earth?**

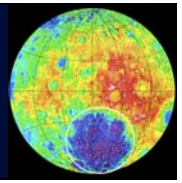
MoonRise determines Earth-Moon history



- **The Moon bears witness to 4½ billion years of Solar System history.**
- **Among the events it records is the timing of the intense bombardment of Earth and Moon 3.9-4.0 billion years ago.**
- **This was a critical period in Earth history:**
  - Life beginning to gain a foothold
  - Formative years of Earth's continents
- **The heavy bombardment at that time as recorded on the Moon was one of the most important events in Solar System history and affected all the terrestrial planets.**
- **MoonRise tests the Cataclysm hypothesis by determining the age of the oldest and largest impact basin on the Moon.**

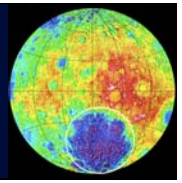
Through MoonRise, we would gain a better understanding of the effects of impact bombardment on surface environments, including habitability, of planets in the inner Solar System.

Mission Overview

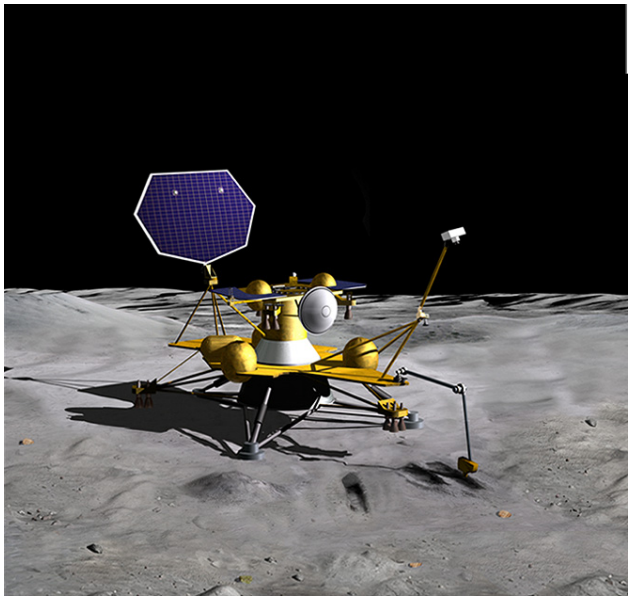


- Proposed launch in 2016
- Propose to land in the interior of the South Pole-Aitken Basin on the Moon's far side, while a dedicated satellite provides essential command and control coverage
- Propose to collect samples (at least 1 kilogram)
  - Emphasize return of thousands of small rocks, which can be dated
- Sample materials would be transferred to a sample return canister, returned to Earth, and recovered at the Utah Test and Training Range, following the STARDUST example
- MoonRise samples would be available for study by the scientific community worldwide and for many years in the future

Mission Feed Forward Overview

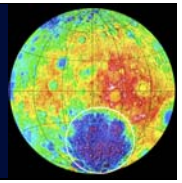


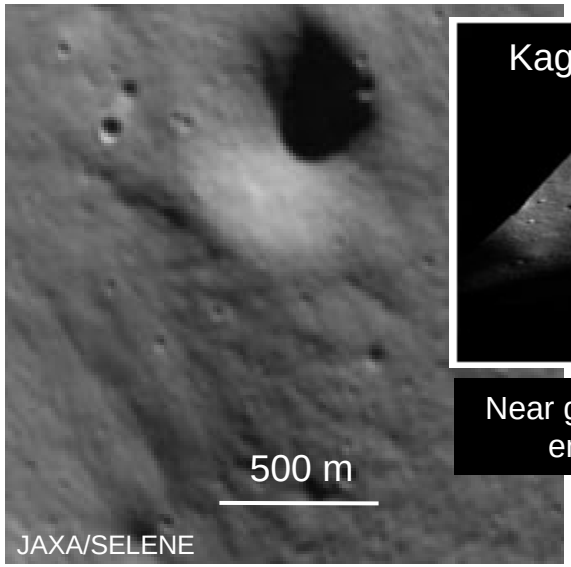
- **MoonRise would be the first US robotic sample-return mission from the surface of another planetary body.**
- **MoonRise capabilities would be applicable to potential future Mars sample return missions**
- **MoonRise would demonstrate a state-of-the art lunar lander to deliver a large payload to the surface of the Moon for future in situ space exploration missions.**

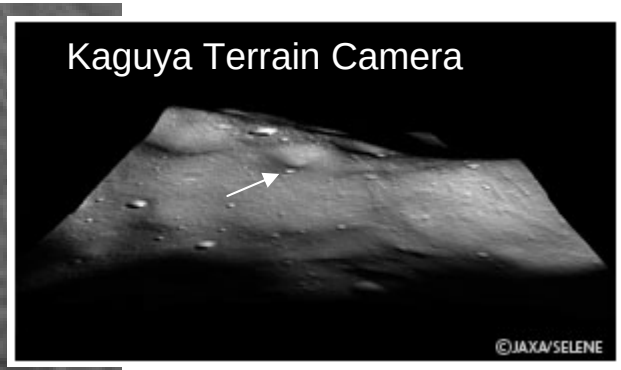


- **In-situ sample acquisition and transfer would demonstrate surface robotic operational capabilities applicable to future lunar exploration missions**

MoonRise leverages new lunar orbital datasets with US and International Partners

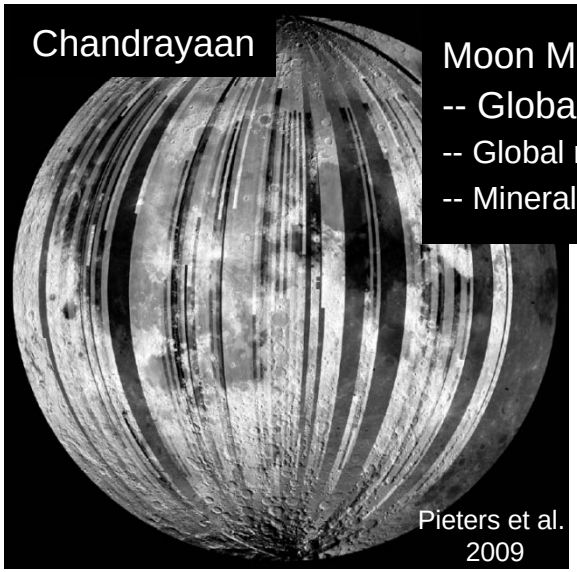




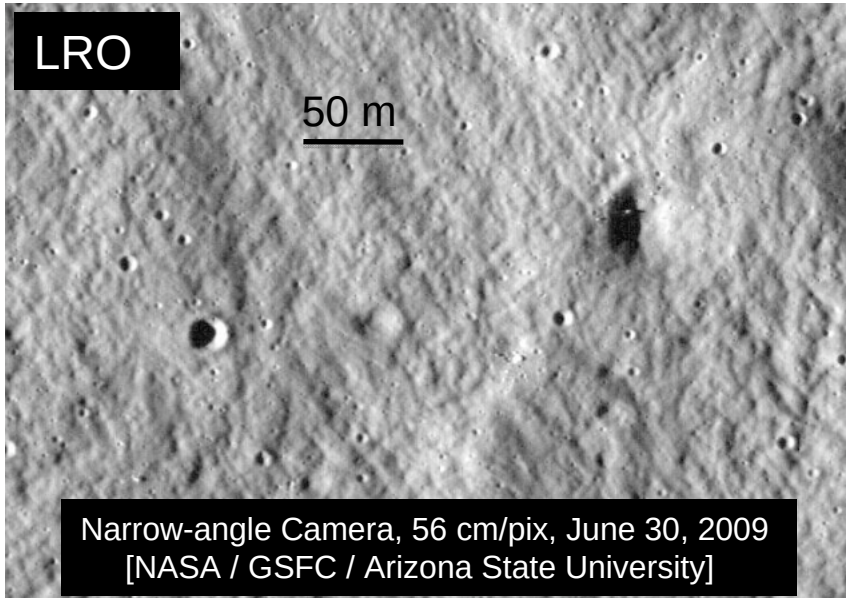


Near global coverage obtained prior to end of mission June 11, 2009

MoonRise would be the logical next step in exploration, now that recent orbital missions have provided imaging and compositional data to support selection of sites that are optimal for science and safe for landing.

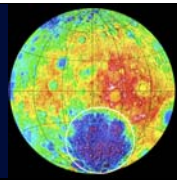


Moon Mineralogy Mapper
-- Global Coverage
-- Global mode 140 m/pix
-- Mineralogy of SPA Basin



Narrow-angle Camera, 56 cm/pix, June 30, 2009
[NASA / GSFC / Arizona State University]

MoonRise Concluding Points



- **MoonRise would address key Solar System Science Objectives as stated in the 2003 NRC Decadal Survey for Solar System Exploration and re-validated in NRC 2007 “NOSSE” report**
- **MoonRise was recognized as a New Frontiers mission by the 2003 Decadal Survey, with the potential of a “paradigm shift” in our understanding of the evolution of the Solar System**
- **MoonRise would address also key objectives for the exploration of the Moon**
- **MoonRise would be a pathfinder for automated sample return from planets and moons in the Solar System**
- **MoonRise would develop a medium-size lunar lander that can deliver a large scientific payload to the lunar surface for potential future NASA lunar robotic missions**
- **The MoonRise proposal, currently in a Phase A concept study stage, would represent a key milestone in the international scientific exploration of the Moon**

Parting Thoughts

- The Apollo Program demonstrated the importance of returned samples in dispelling myths and in establishing a modern understanding of the Moon, and of solar system evolution
- The Apollo Program helped develop geochemistry analytical techniques and a new approach to planetary science
- The techniques have revolutionized subsequent (and current) research on lunar samples, meteorites and terrestrial samples
- It would be exciting for old-timers and for new-timers to obtain new samples from the Moon and to investigate the validity of the Terminal Lunar Cataclysm (TLC) hypothesis and its implications for the evolution of the solar system